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CONCURRENT RESEARCH ON HIGH GRAVITY (g) COMBUSTION WITH ENABLING MATERIALS

(LRIR: 99PR12COR)

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SUMMARY/OVERVIEW

A gas turbine combustor concept that uses high g-loading in the circumferential cavity is being tested at AFRL to provide the foundation for development of a low-emissions, ultra-compact, high performance combustion system for future military and commercial aircraft. This work comprises experimental testing and modeling and simulation of different high g-loaded combustion cavities. Initial tests indicate that, by using highly swirling flows, the combustor performance can be enhanced in the form of improved combustor efficiencies at reduced combustor length. Understanding the impact of high g-loading on the pollutant emissions, operability limits, and combustor durability are three major areas where the AFOSR program will progress the scientific understanding of the physical processes involved in this novel combustion system.

TECHNICAL DISCUSSION

This AFOSR-sponsored work addresses fundamental combustion issues that will lead to the development of a revolutionary propulsion system that operates on a highly efficient, near constant temperature (NCT) cycle instead of the constant pressure cycle of today's engines. Such a propulsion system could provide increased power extraction, thrust augmentation, and specific thrust (ST) enhancements. A key technology essential for the development of a propulsion system that operates on a NCT cycle is an ultra-compact combustion (UCC) system that will efficiently add heat between the turbine stages and is constructed of advanced, light-weight ceramic-matrix composites (CMC) materials. This combustor has been referred to in the literature as an inter-turbine burner (ITB).

The AFRL team has been working on the premise that high g loading can provide benefits compared to conventional gas turbine combustion systems. A concept design for a high-g combustion system that can serve as a main combustor or as an ITB has been completed however, understanding of the combustion process at high g-loading conditions is necessary. The AFRL team is focused on what we believe are the key combustion issues. (1)What are the fundamental processes that control combustion in a highly accelerated (high-g) flows? (2) How does swirling flow from the main air supply impact the cavity combustion process? and (3) Can we integrate CMC vanes into flow path while turning the flow? (4) How does vitiated flow impact the high g combustion process? In this abstract, we will focus on experimental results related to vitiated flow.

Approach

Vitiated Flow Experiments: The vitiator used for these experiments was originally designed to be used in fundamental augmentor combustion research activities to simulate the core flow of an augmented

turbofan engine burning JP8 fuel. The vitiator operates at pressures of 50 psig to facilitate efficient combustion. The major components of the vitiator are shown in Fig. 1, where the vitiator is installed in front of the ITB test rig. Air is supplied to the front end of the vitiator plenum section that houses the single fuel injector/swirler module. The module employs a "cyclone" type swirler. The fuel injector is a hollow cone peanut type pressure atomizer that has an air cooled jacket surrounding the fuel feed tube to reduce potential for coking. The air delivered to the vitiator is heated via electric heaters to temperatures near 600°F with typical pressure drops across the swirler of 6-8%. The dome plate holding the swirl cup is effusion-cooled with a thermal barrier coating (TBC) on the dome surface. The combustor liner is an uncooled pipe section that is over-designed to handle the pressure-temperature combination. The vitiator combustor is ignited by a propane/air torch that incorporates a conventional automotive spark igniter to initiate the ignition of the fuel-air mixture in the torch.

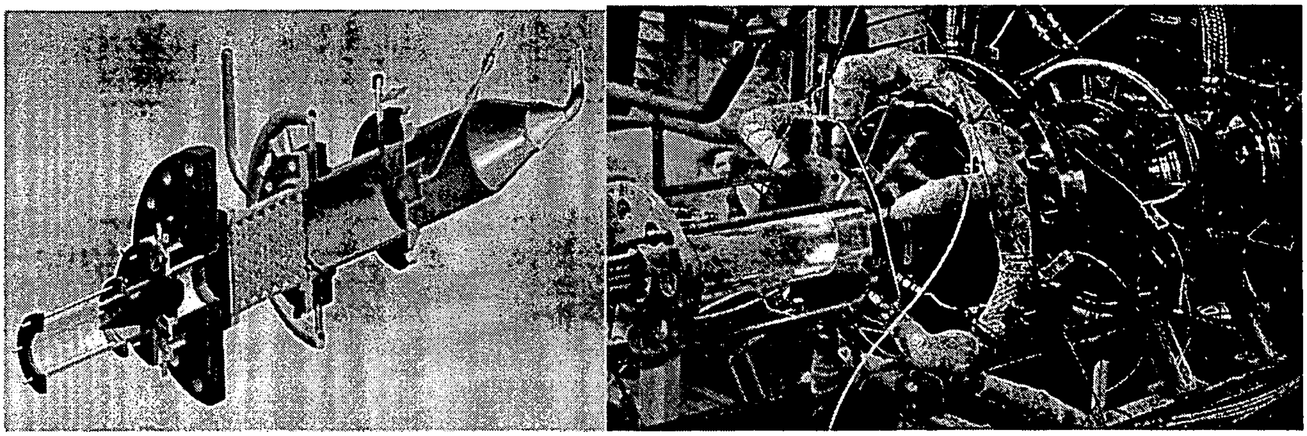

Figure 1: High g Combustor with Vitiator.

Combustion Stability Results: Combustor lean blowout (LBO) was investigated for the different configurations. The OFAR at LBO was plotted against the cavity g-loading and cavity loading parameter (LP). To determine cavity g-loading, estimates of the tangential velocity (V_{tan}) were estimated from the expression;

$$g = \frac{V_{tan}^2}{g_c r_{cav}} \qquad \text{Eq. (1)}$$

is used to calculate the g-loading. These tests were run at atmospheric pressure and 500 °F inlet air temperature.

Recent work[1] with the UCC/ITB suggests a dependent behavior on reaction temperature and/or liquid fuel atomization, in addition to g-loading effects. As Yonezawa et. al[2] suggested by continuing Lewis[3] work through introducing the observations for flame propagation by Chomiak[4] for turbulence enhancement through the generation and movement of non-premixed buoyant "bubbles", or eddies, of non-premixed and partially-premixed reactants, and burned reactants, such that the burning velocity (S_b),

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[1] Zelina, J., Sturgess, G. J., Mansour, A., and Hancock, R. D., "Fuel Injection Design for Ultra-Compact Combustor," ISABE 2003-1089.
[2] Yonezawa, Y., Toh, H., Goto, S and Obata, M., "Development of the Jet-Swirl High Loading Combustor," Paper No. AIAA-90-2451, *26th. AIAA/SAE/ASME/ASEE Joint Propulsion Conference,* Orlando, Florida, 1990.
[3] Lewis, G.D., "Centrifugal-Force Effects on Combustion," proc. *14th. Symposium (International) on Combustion,* The Combustion Institute, 1973, pp. 413-419.
[4] Chomiak, J., "Dissipation Fluctuations and the Structure and Propagation of Turbulent Flames in Premixed Gases at High Reynolds Numbers," Sixteenth Symposium (International) on Combustion, The Combustion Institute, 1977, pp. 1665-1673.

$$S_b = \frac{\rho_u}{\rho_b}\sqrt{Rg} \qquad \text{Eq. (2)}$$

where the density gradient is worked on by the centrifugal force generated through the swirl. So, at fixed radius (R) and operating pressure, and neglecting differences in gas constants,

$$S_b \propto \frac{T_b}{T_u}\sqrt{g} \qquad \text{Eq. (3)}$$

T_u is taken as the air inlet temperature and T_b ideally should be a measured gas temperature at the cavity exit, but here is taken as the adiabatic flame temperature calculated for JP-8/air from an equilibrium chemistry code. When found in these ways the ratio T_b/T_u represents a maximum value. Therefore, if combustion efficiency is assumed to be proportional to S_b, and when data is plotted in terms of $(T_b/T_u)(g)^{1/2}$ as the abscissa, the systematic variation in the conditions for the maximum combustion efficiency should be eliminated, and improved correlation of combustion efficiency data would be expected, for cavity-only burning and if there are no physical effects controlling the combustion process. This correlation $((T_b/T_u)(g)^{1/2})$ will be referred to as the Swirl Parameter (SP) In these experiments, very small flow number (FN) fuel injectors were used, indicating that the atomization level was very good (~20-40 micron drops), removing this physical effect from the data.

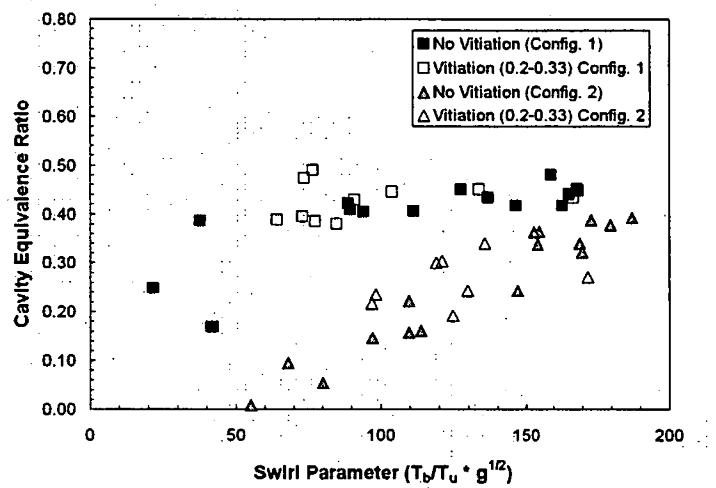

Figure 2: Cavity equivalence ratio at blowout as a function of the Swirl Parameter (SP) for two designs and vitiation level.

In Fig. 2, ϕ_{cav} at blowout is plotted as a function of SP. Configuration 1 and Configuration 2 (variation in injector airflow) are shown, where the vitiation level in the main flow stream varies from zero to $\phi_{vit} = 0.33$. It is clear from the data that Configuration 2 (reduced injector airflow) blowout level is superior to the Configuration 1 design. It is also observed that the vitiation level has very little impact on the lean blowout value. This is somewhat expected, since the circumferential cavity is fed with fresh air for all of the data plotted in the figure, and blowout occurs from the cavity. Conditions in the circumferential cavity control the flame stabilization. Notice in Fig. 14 that for both configurations that ϕ_{cav} at blowout is very close to or below flame extinction limits for premixed flames. Incorporated in the design is a geometric feature that was found to provide excellent stability characteristics. Local fuel-rich pockets exist in the circumferential cavity to stabilize the flame.

Combustion Efficiency: Combustion efficiency, determined by gas analysis, is plotted as a function of ϕ_{cav} for different levels of ϕ_{vit} and is shown in Fig. 3. Measurements were collected with a five-element probe that spanned the entire exit plane of the combustor. The probe was located at the trailing edge of the centerbody, about 12 inches downstream from the circumferential cavity. At very lean values of ϕ_{cav}, and low values of ϕ_{vit}, the combustion efficiency is 84-95%. For both configurations, the efficiency increases with increased ϕ_{cav} and approaches 99.9% efficiency near ϕ_{cav} ~1.0. It is also observed that combustion efficiency increased as ϕ_{vit} increased. In fact, for Configuration 1 at ϕ_{cav} ~0.6, the effect of increasing $\phi_{vit} = 0.247$ to $\phi_{vit} = 0.327$ resulted in a combustion efficiency increase from 85% to 99.5%. Since oxygen concentrations are less for the higher vitiated case, the increase in combustion efficiency is

largely due to the increase in main stream temperature (+400°F), whereby quenching of CO and UHC is minimized.

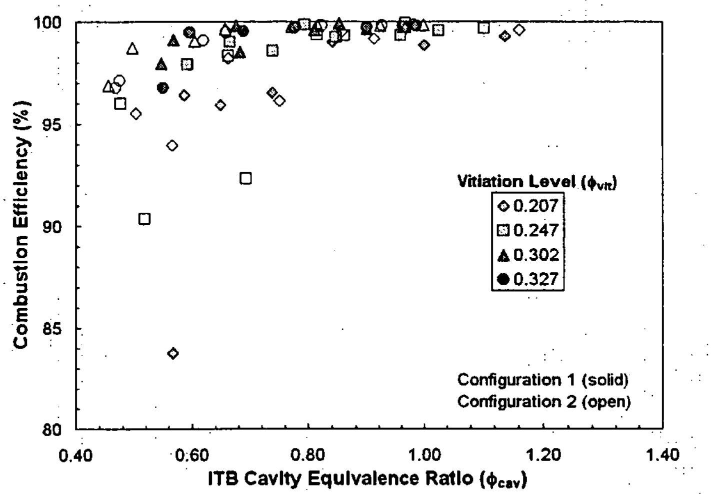

Figure 3: Combustion efficiency as a function of ITB cavity equivalence ratio and vitiation level for the two configurations.

Future Work: Several experiments are planned for the UCC/ITB concept and these include:

- Investigation of gaseous fuel (propane) to study the effects of atomization on the high g combustor performance
- Develop cavity design methodology by changing cavity aspect ratios and mapping the combustion performance
- Study the impacts of swirl caused by the turbine vanes on cavity combustion
- Investigate new radial vane cavity transport designs.
- Use of laser diagnostics through quartz windows located along the circumferential cavity to study the high g combustion and flame stability mechanisms in the cavity.

The modular configuration that will be used for these tests is shown in Fig. 4. The transparent area is the current circumferential cavity where air and fuel are injected. The yellow vanes represent realistic vane designs and the radial cavities will be studied to determine their effectiveness on transporting the circumferential cavity mixture to the main flow.

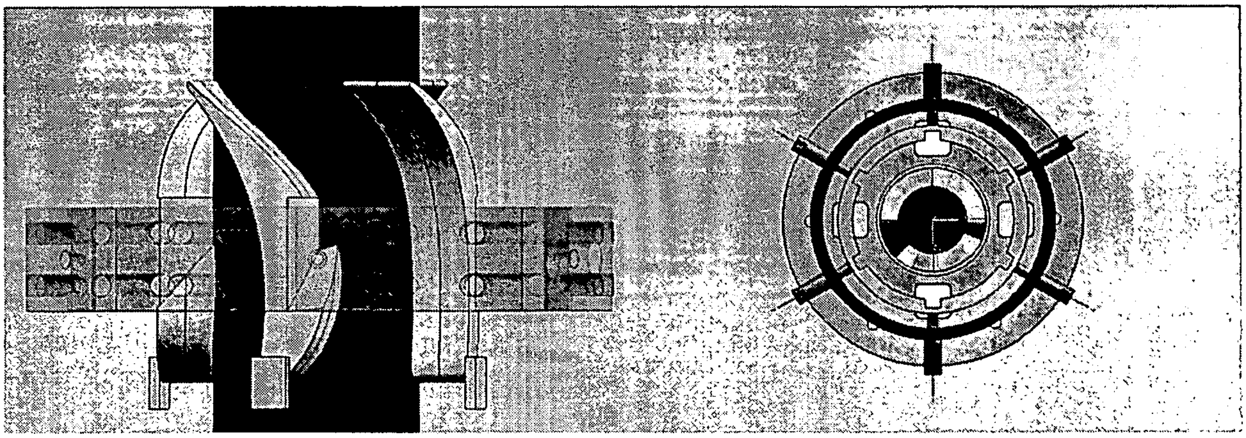

Figure 4: Modular combustor design to investigate cavity geometry, atomization effects, and impact of main swirl on cavity combustion.

External Collaboration: AFRL continues to collaborate with Air Force Institute of Technology on specific high g combustor problems. AFRL is actively involved with industry to transition compact, high g combustor concepts to industry. Currently, AFRL is working directly with three major engine companies, along with smaller businesses to incorporate design concepts. We continue to look for opportunities to start 6.2 programs utilizing our 6.1 results to demonstrate an UCC/ITB. This collaborative approach provides a clear transition path for the 6.1 research and would provide additional funds needed to demonstrate a turbine burner concept.